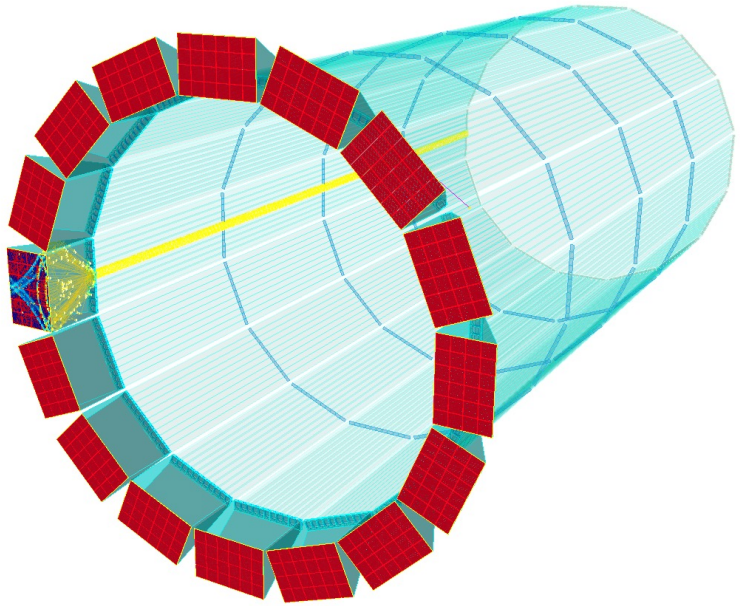
eRD103: The High-Performance DIRC

Directed R&D Proposal to Mitigate Key Risks for the EIC Project Detector



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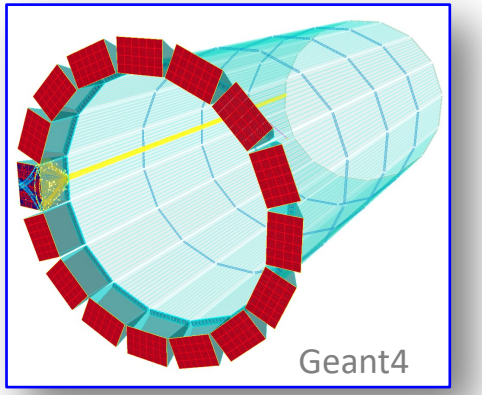
HPDIRC ACTIVITY OVERVIEW

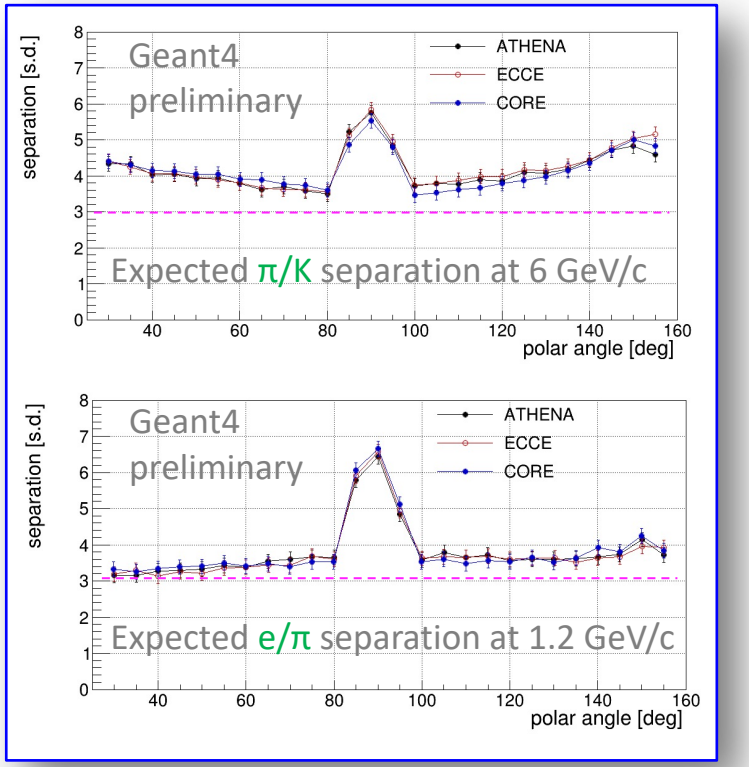
Primary eRD103 Objectives:

- To validate the PID performance of a cost-optimized hpDIRC design for the EIC project detector with a vertical-slice prototype in a particle beam by FY24.
- To minimize hpDIRC risks and to realize opportunities and come to clear decisions by the end of FY24.



hpDIRC Concept:

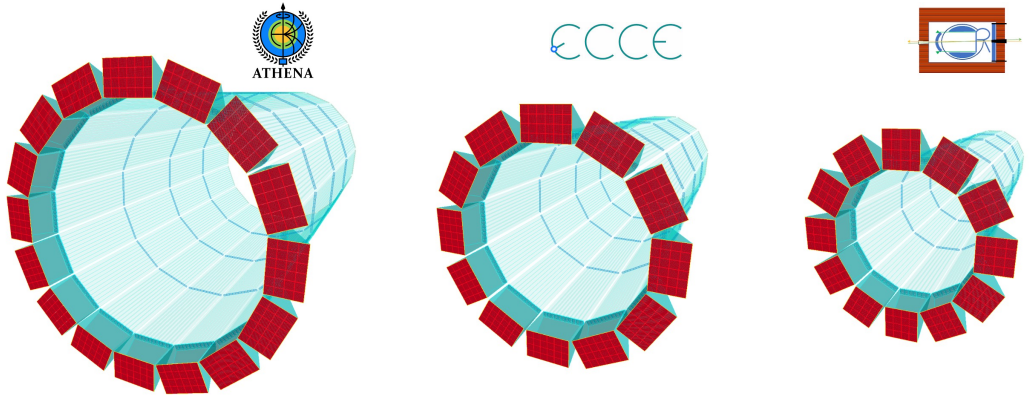
- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Design based on BaBar DIRC, R&D for SuperB FDIRC, PANDA Barrel DIRC
- Radiator/light guide: narrow fused silica bars (radius/length tuned for all EIC proposals)
- Innovative 3-layer spherical lenses
- Compact fused silica prisms as expansion volumes
- Fast photon detection using small-pixel MCP-PMTs *(eRD110)* and high-density readout electronics *(eRD103/eRD109)*
- Detailed Geant4 simulation: ≥ 3 s.d. π/K separation at 6 GeV/c



HPDIRC R&D PRIORITIES

hpDIRC is the baseline hadronic PID system for the detector barrel in all three EIC proposals

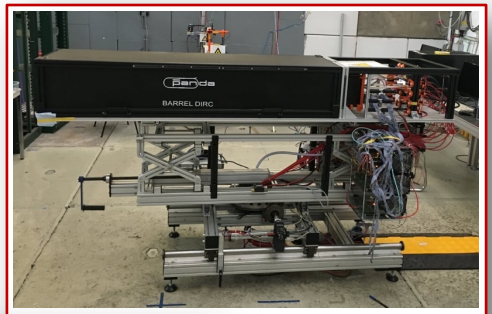
- Baseline: hpDIRC with reused BaBar DIRC bars
- Demanding project schedule: CD-2 (1/2023), CD-3 (3/2024)



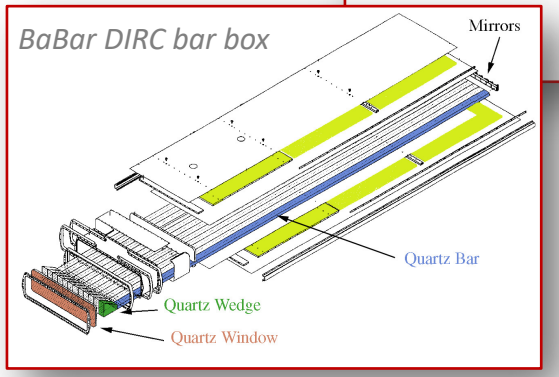
Geant4: hpDIRC designs to scale

R&D Priorities: Minimize risks, realize opportunities

- Technical risk: small pixel photon sensor and fast readout electronics performance
- Technical risk/opportunity: reuse of BaBar DIRC bars
- Technical risk: hpDIRC PID baseline design validation
- Technical risk/opportunity: narrow bars with wide plate hybrid design
- Opportunity: cost/performance optimization



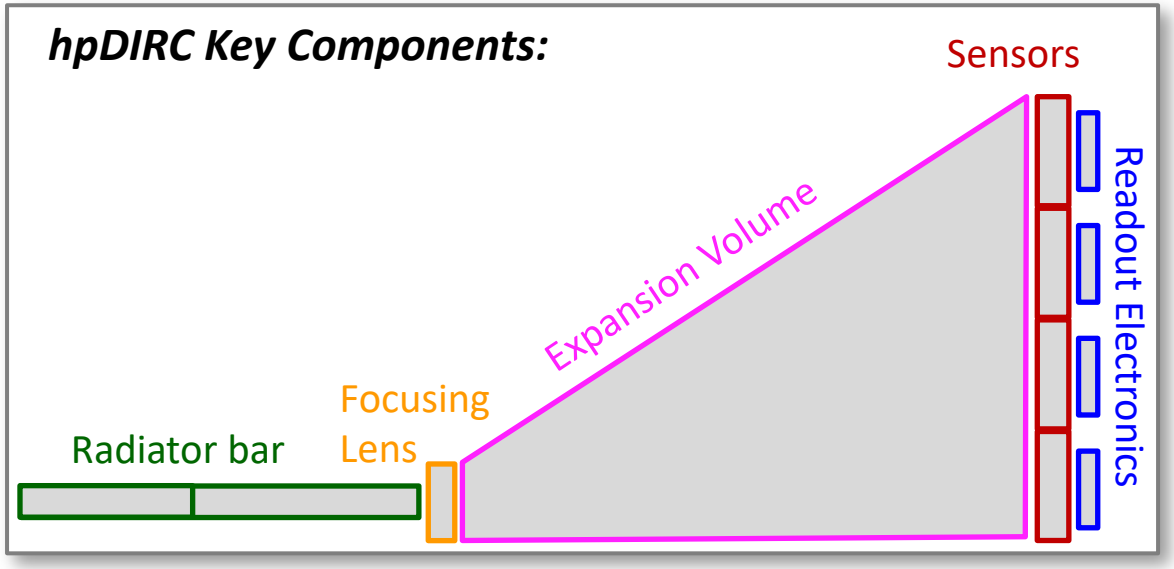
PANDA Barrel DIRC prototype



HPDIRC R&D PLAN

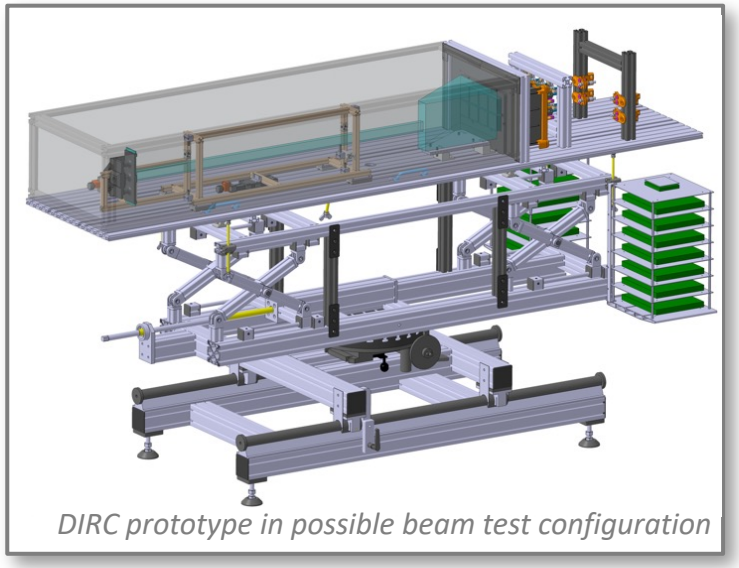
FY 22

- Validation of BaBar DIRC radiator bar reuse option
- Development and adaptation of readout electronics
- Assembly and integration of initial prototype into CRT with tracking and timing detectors
- Development of DAQ and 3D tracking code
- Cost/performance optimization of design in simulation



FY 23

- Incremental upgrade of hpDIRC prototype
- Evaluation of sensors and readout electronics in hpDIRC prototype
- Evaluation of initial prototype, tracking/timing/DAQ in particle beam



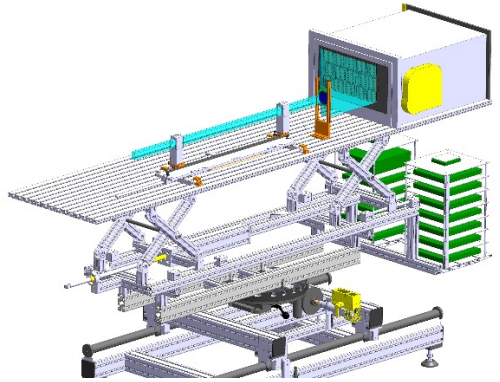
DIRC prototype in possible beam test configuration

FY 24

- Evaluation of the optimized sensor arrangement and radiator/focusing options (bar/plate hybrid design with matching focusing lens) with final prototype in particle beam
- Conclusion of prototype program with final cost/performance-optimized design

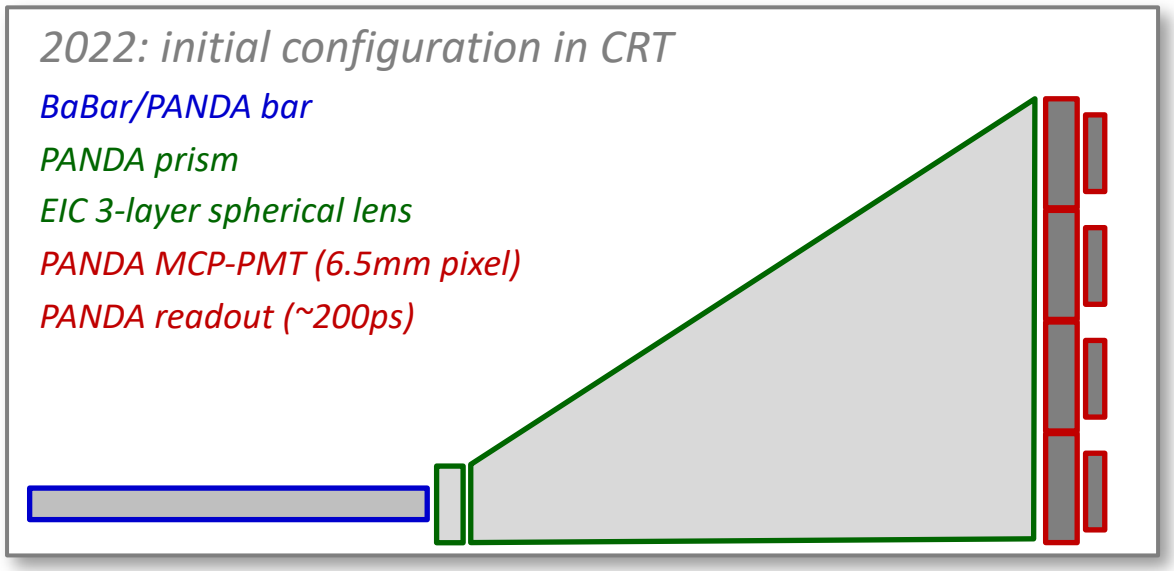
HPDIRC R&D FY22 HIGHLIGHTS

- Validation of the BaBar DIRC bar reuse:
  - Evaluate quality of disassembled bars and finalize disassembly strategy
  - Build and operate QA laser setup to measure mechanical and optical quality of the bars
- hpDIRC design studies in simulation:.
  - Determine number of required sensors and optimize arrangement on detector plane
  - Study options for fused silica lightguide between the BaBar DIRC bars and prism: short narrow bars or a short plate and investigate matching type of focusing configuration
- Incremental development of hpDIRC prototype:
  - Set up Cosmic Ray Telescope at SBU with tracking and timing detectors, including 3D tracking algorithm, prepare for use in future beam tests at Fermilab, integrate hpDIRC prototype
  - Develop a working combination of small pixel sensors and a fast readout system at UH/Nalu to match the unique hpDIRC timing precision requirement
  - Start assembly of EIC hpDIRC prototype with small pixel-size sensors and readout electronics
  - Start procurement of a sufficient number of small-pixel MCP-PMTs for 2023 and 2024 test beam campaigns



hpDIRC Prototype Progression

- Minimize prototype program startup cost, accelerate schedule by starting with reused PANDA components
- Initial hpDIRC prototype based on PANDA DIRC bar, lens, prism, MCP-PMTs, and readout, plus eRD14-funded EIC DIRC prototype focussing lenses
- Modular design will allow incremental replacement and testing of components
- Integrate prototype into new Cosmic Ray Telescope setup with tracking and timing detectors for future use in beamline



- Functional CRT-hpDIRC configuration makes it possible to develop and test 3D tracking and event timing methods with real data and prepare entire setup for beam test
- Test bed for small-pixel MCP-PMTs with UH/Nalu readout electronics with Cherenkov photons

HPDIRC PROTOTYPE PROGRESSION

- Incremental replacement of large-pixel PANDA MCP-PMTs and readout with new small-pixel MCP-PMTs and fast, compact UH/Nalu readout
- First hpDIRC prototype in Fermilab particle beam expected to comprise mix of PANDA and EIC MCP-PMTs and electronics
- Validate tracking and timing detectors and DAQ with particle beam in FY23, extract performance parameters for PANDA and EIC sensor/readout modules

2023: first beam test configuration

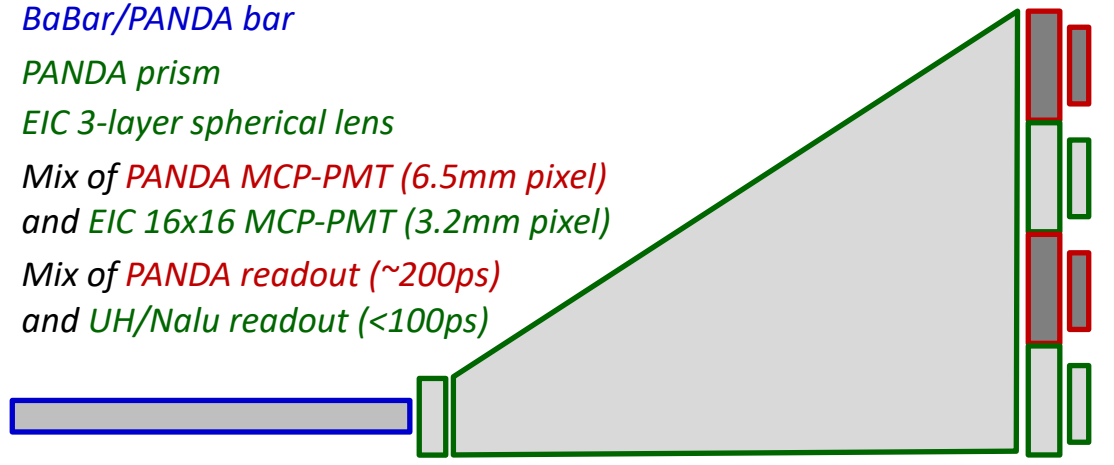
BaBar/PANDA bar

PANDA prism

EIC 3-layer spherical lens

Mix of PANDA MCP-PMT (6.5mm pixel) and EIC 16x16 MCP-PMT (3.2mm pixel)

Mix of PANDA readout (~200ps) and UH/Nalu readout (<100ps)



HPDIRC PROTOTYPE PROGRESSION

- Finalize prototype configuration based on simulation results narrow bar or bar/plate hybrid with matching lens and optimized sensor coverage
- Complete incremental replacement of PANDA components with EIC components (sensors, electronics)
- Validate performance parameters with particle beam in FY24
- Conclusion of prototype program with final cost/performance optimized design

2024: final beam test configuration

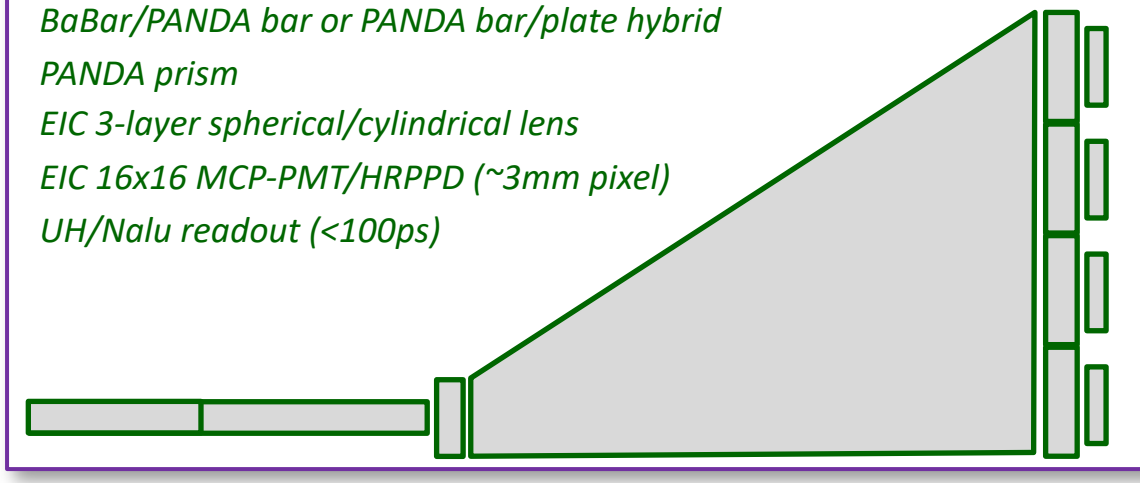
BaBar/PANDA bar or PANDA bar/plate hybrid

PANDA prism

EIC 3-layer spherical/cylindrical lens

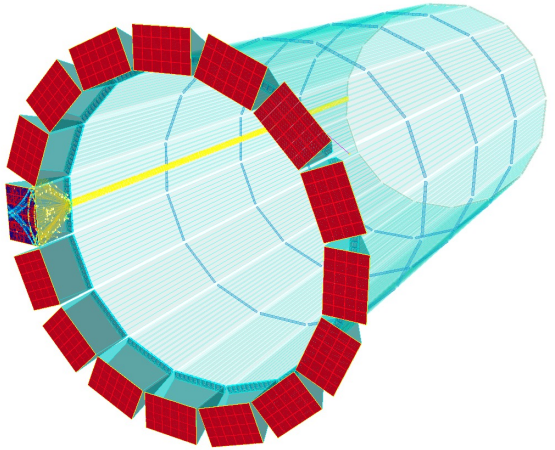
EIC 16x16 MCP-PMT/HRPPD (~3mm pixel)

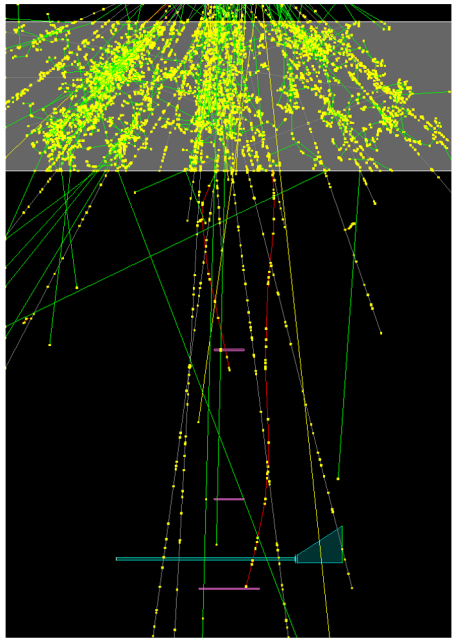
UH/Nalu readout (<100ps)



HPDIRC R&D FY22 MILESTONES

- Optical DIRC lab for BaBar DIRC bar QA ready (JLab/ODU, Q2/2022)
- Assembly of Cosmic Ray Telescope in SBU DIRC lab complete (SBU/ODU/CUA, Q2/2022)
- Mechanical integration of initial hpDIRC prototype into CRT achieved (SBU/CUA/GSI, Q2/2022)
- Complete QA of bars from first disassembled BaBar DIRC bar box, decision about further disassembly strategy (ODU, Q3/2022)
- Initial DAQ and track reconstruction software ready and tested (CUA/SBU, Q3/2022)
- Prototype of readout electronics available for tests with small-pixel MCP-PMT in Hawaii (UH/Nalu, Q2/2022)
- Completed evaluation of cost/performance optimized EIC DIRC design options in simulation (CUA/GSI, Q4/2022)
- Start integration of first new small-pixel MCP-PMT/readout electronics modules into hpDIRC prototype at SBU (CUA/UH/Nalu, Q4/2022)





HPDIRC FY22 BUDGET REQUEST

FY 22 Plan:

- hpDIRC Cost/Performance design optimization
- Incremental development of hpDIRC prototype:
  - Assembly and operation of CRT setup
  - Initial prototype with PANDA DIRC readout
  - Development of fast readout electronics
  - Procurement of sensors (based on eRD110 findings)
- Validation of the BaBar DIRC bar reuse

Budget request:

- ⇨ Extend CUA PostDoc contract
- ⇨ Travel for CUA, materials for SBU
- ⇨ Materials and travel for CUA, GSI
- ⇨ PostDoc and materials for UH and Nalu
- ⇨ Sensors for FY23 and FY24 testbeam campaigns
- ⇨ PostDoc for ODU (plus, possibly, materials)

Notes

- Start of funding for UH PostDoc by Jan 2022 is essential to avoid loss of expertise.
- Funding for readout electronics development could be managed through eRD109 instead.
- Funding for DIRC lab equipment may become available from JLab.

Item	Institution	Requested
Postdoc (50%) hpDIRC software	CUA	\$80k
Prototype Equipment	CUA	\$10k
Sensors for 2023 EIC hpDIRC Prototype (CUA)	CUA	\$140k
Travel to DIRC lab at SBU	CUA/GSI	\$30k
Postdoc (50%) QA of BaBar DIRC bars	ODU	\$80k
Equipment for QA of BaBar DIRC bars	ODU	\$50k*
*(in case direct funding from JLab is unavailable)		
CRT readout electronics	SBU	\$20k
CRT materials	SBU	\$15k
Postdoc (50%) readout electronics	UH	\$60k**
Test-bench/readout board assembly	UH	\$15k**
ASIC and engineering support	Nalu	\$25k**
**(funding for the hpDIRC electronics development may be coordinated via eRD109)		
Total		\$525k

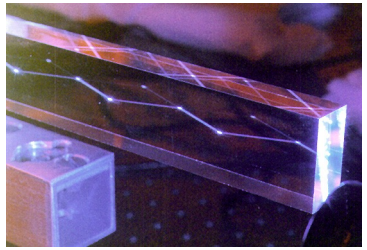
HPDIRC FY22 BUDGET REQUEST

Item	Institution	Requested
Postdoc (50%) hpDIRC software	CUA	$80k
Prototype Equipment	CUA	$10k
Sensors for 2023 EIC hpDIRC Prototype (CUA)	CUA	$140k
Travel to DIRC lab at SBU	CUA/GSI	$30k
Postdoc (50%) QA of BaBar DIRC bars	ODU	$80k
Equipment for QA of BaBar DIRC bars	ODU	$50k*
*(in case direct funding from JLab is unavailable)		
CRT readout electronics	SBU	$20k
CRT materials	SBU	$15k
Postdoc (50%) readout electronics	UH	$60k**
Test-bench/readout board assembly	UH	$15k**
ASIC and engineering support	Nalu	$25k**
**(funding for the hpDIRC electronics development may be coordinated via eRD109)		
Total		$525k

Institution	CUA	ODU	SBU	UH	Nalu	**Total**
Requested	$260	$130k*	$35k	$75k**	$25k**	$525k

BaBar DIRC Bar Box Disassembly

Technical risk/financial opportunity: reuse of BaBar DIRC bars

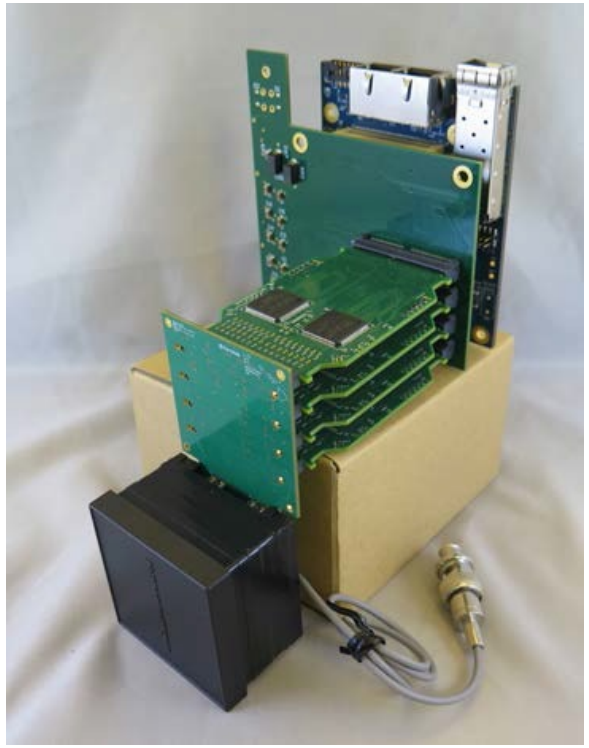


- BaBar DIRC disassembled in 2010, SLAC/DOE made DIRC bars available for reuse
- Potentially saves up to $5M in cost, reduces technical and schedule risk
- Full-size bar boxes are too long, do not fit into EIC central detector,
  wedges deteriorate resolution: need to disassemble bar boxes for reuse
- Eight bar boxes located at SLAC, awarded to JLab for potential use in EIC
  Four additional unmodified bar boxes already at JLab for GlueX DIRC since 2018, potentially available
  For reasonably high yield of high-quality bars: number of bars sufficient for EIC project detector
- Advanced discussions with SLAC DIRC experts, plan to open bar boxes and decouple bars in SLAC DIRC lab using heat gun,
  disassembly to start in early 2022, funding for contract with SLAC assumed to be available from JLab (R. Ent)
- R&D is required to finalize and validate procedure and to assess cost and technical risk
  DIRC lab at JLab or ODU needed to measure quality of bar surfaces with laser system, validate disassembly method.
  Risks: deterioration after 20+ years in bar box, contamination of bar surfaces from opening of box and drom heat gun disassembly.
  Requesting funding for DIRC lab equipment – unless funds are made available from JLab (R. Ent, discussion ongoing)
  Requesting funding for 6 months PostDoc labor to set up DIRC lab and perform initial evaluation measurement in FY22.

READOUT ELECTRONICS

hpDIRC unique readout requirements:

- All three leading sensor candidates (MCP-PMT, MAPMT, SiPM) share:
  - Large number of small pixels
  - Fast single photon timing
  - Relatively high photon rates and sensor occupancies
- Readout electronics must maintain 60-100ps timing resolution, matching sensors
- Performance requirements for e.g. triggerless streaming, data reduction, bandwidth, latency and throughput must be achieved while simultaneously meeting technical requirements for other critical factors such as e.g. power consumption, integration issues at the detector front end along with robust electromechanical sensor interfaces and biasing
- There is **NOTHING** on the market that meets all requirements and scales well
- Test all sensors with minimal effort on electronics and a common readout solution



Requesting funding for 50% PostDoc and fabrication cost at UH and equipment and engineering support from Nalu.

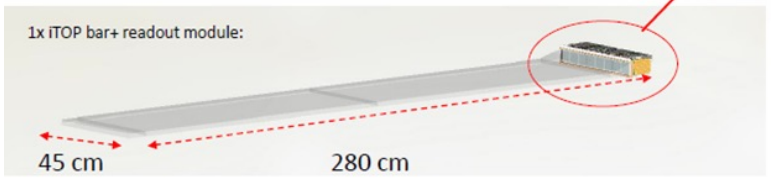
READOUT ELECTRONICS

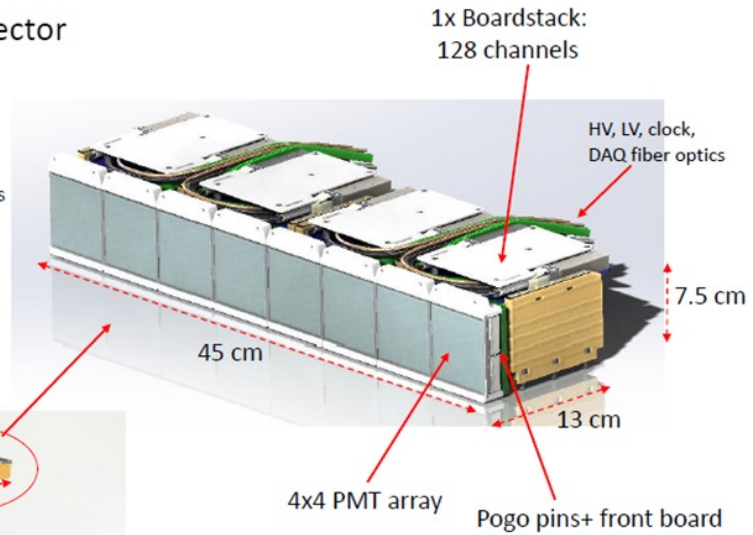
The close collaboration between Nalu and UH was established several years ago in the design, fabrication and deployment of the Belle II DIRC TOP detector (below left), which shares many similarities to the hpDIRC.

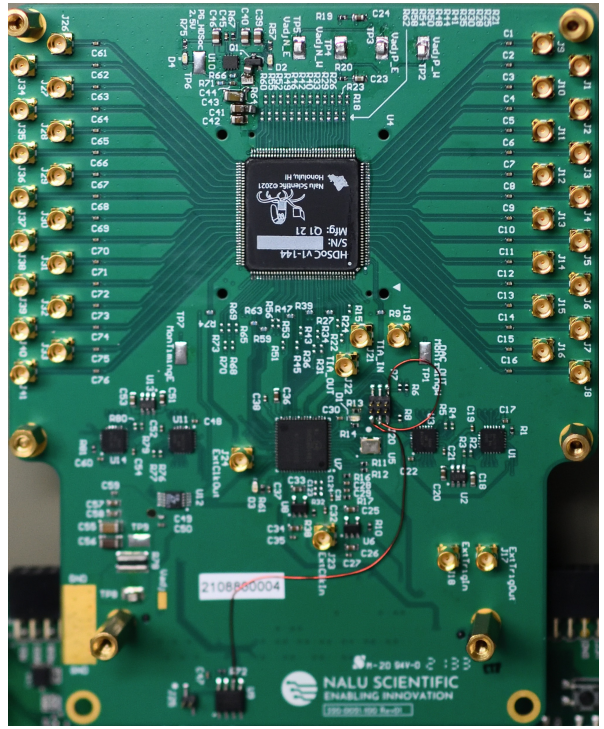
The TOP project was awarded the DOE's Project Management Achievement Award in 2017, and was completed two months ahead of schedule and under budget while meeting or exceeding all objective Key Performance Parameters.

Nalu's HDSoC ASIC (32-chnl test board below right), currently under development with a DOE Phase II SBIR, is well matched to EIC-PID's performance and technical requirements and the plan is to continue to evolve the platform to systematically address the challenges inherent in ultimately bringing the full EIC detector(s) online and ready for physics data-taking.

- 8192 channels of readout for iTOP subdetector
- 16 quartz bars, 1x module/bar
  - 1x readout module:
    - Photons in, DAQ data out
    - PMTs, interconnectes, amps, ASICs, FPGAs, heatsinks
    - 45 cm x 7.5 cm x 13 cm
    - 512 channels
    - Dense and compact- operates inside magnet
- All modules installed in detector







READOUT ELECTRONICS

FY'22- Develop and de-risk electronics

- Use 32ch HDSoC eval card as a building block to readout a subset of channels of various sensors (Photonis, HRPPD, Photek…)
- Nalu will provide 32 ch HDSoC eval board+engineering knowhow and FW/SW customization
- UH will provide post-doc and lab for testing and data analysis - prepare for cosmic telescope testing (for 32 or 64ch)
- Nalu will develop and fab the 64 channel HDSoC using Phase II SBIR funds
- Preliminary design for a modular integrated readout solution.

FY'23 - Prepare for summer '23 beam tests

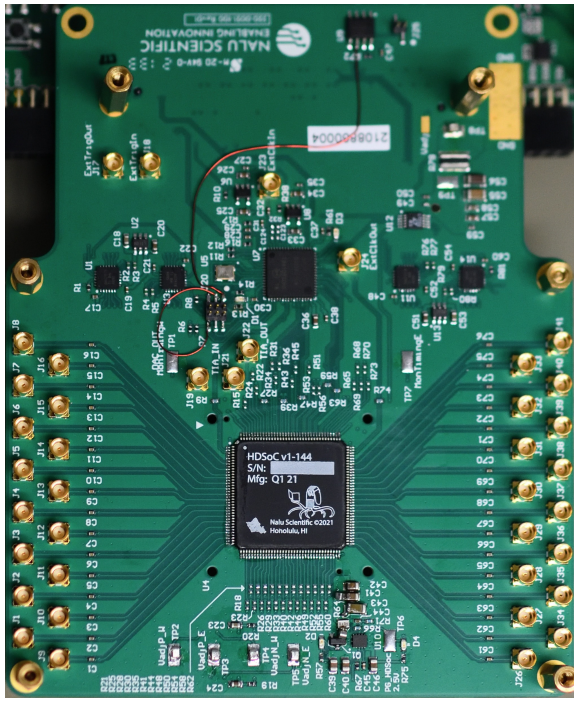
- Design and fab sensor specific 4-6k channel electro-mechanically integrated readout based on 64ch HDSoC (with design reuse in mind) and prepare for beam tests - contingent on proper budget allocation and prompt start on day one of FY23.
- Perform beam tests, analyze data and present results
- Perform a study on ASIC customization for various subdetectors (SBIR funds slightly more generic R&D than detector specific work).

FY'24-25- ASIC and electronic customization

- Customize HDSoC for speed (60ps resolution), data rates, processing capacity of each detector.
- Fab, package, test and qualify - rather low risk given underlying ASIC is mature
- Design high channel count subdetectors using customized ASICs.

FY'26-27 - Mass production

- Design for cost, dedicated ASIC fab and packaging.
- Board level designs tweaked for cost and sent to contract fab/assy houses
- Calibration, qualification, installation.



Readout electronics schedule matches hpDIRC timeline

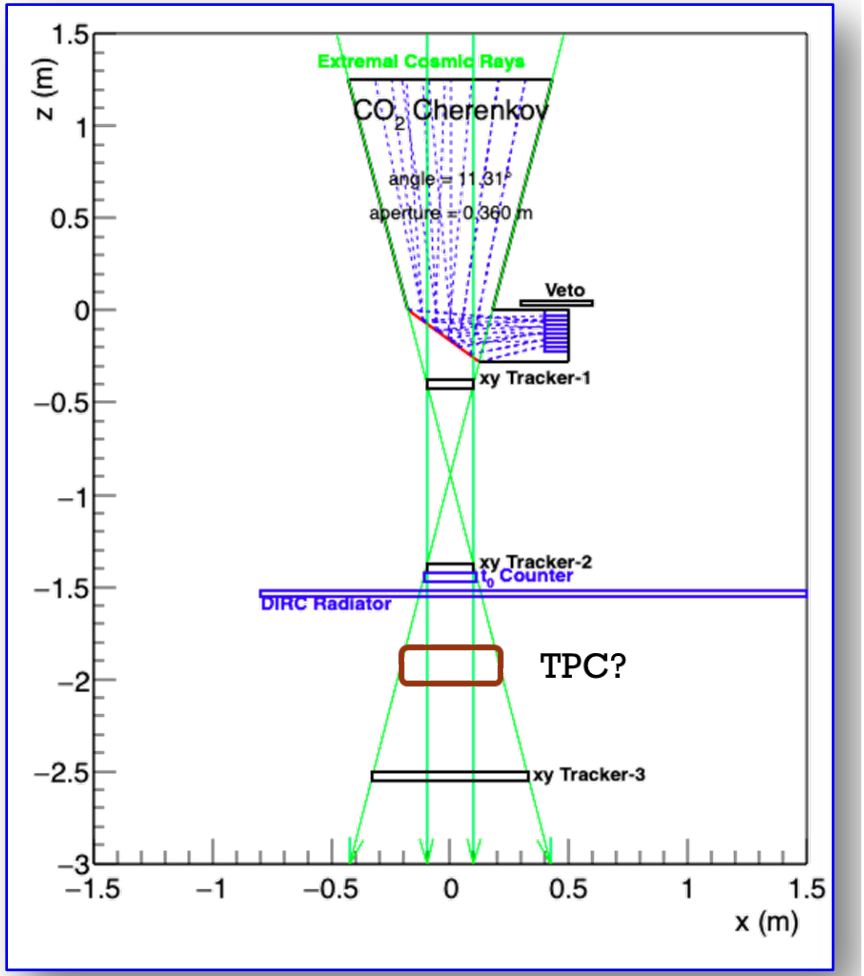
HPDIRC PROTOTYPE: DEVELOPMENT AND VALIDATION

Opportunity: Preparation of Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Work on mechanical and readout aspects of hpDIRC prototype
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan

Current design:

- Momentum selection: new CO_2 Cherenkov threshold tagger (> ~3.5 GeV/c)
- 3D tracking: two GEM tracker stations (from sPHENIX) above and below DIRC bar, potentially combined with TPC prototype
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: MCP-PMT/LAPPD or PICOSEC-Micromegas counter
- Mechanical design progressing, prototype polar angle rotation foreseen
- Geant simulation package in preparation



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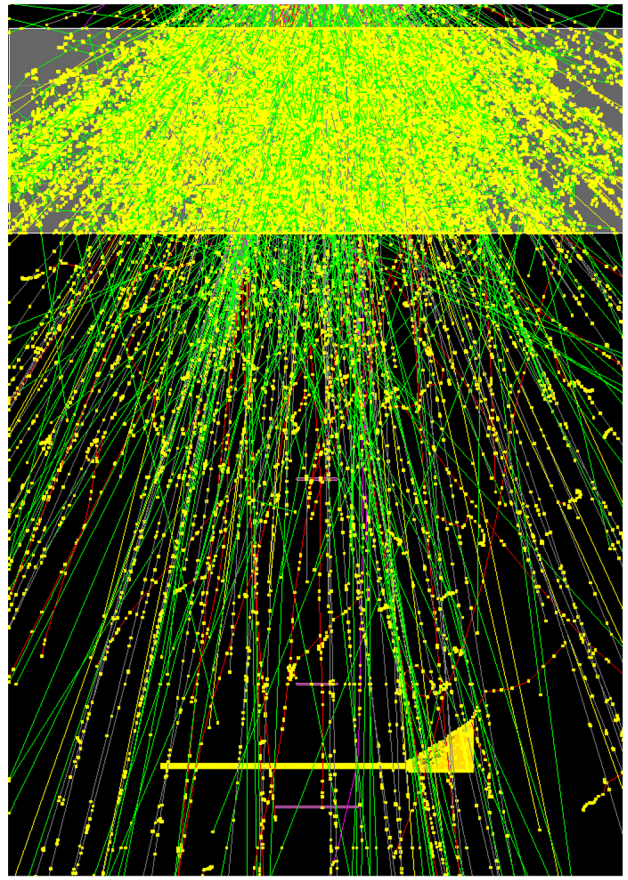
Geant: ~10 seconds of real time



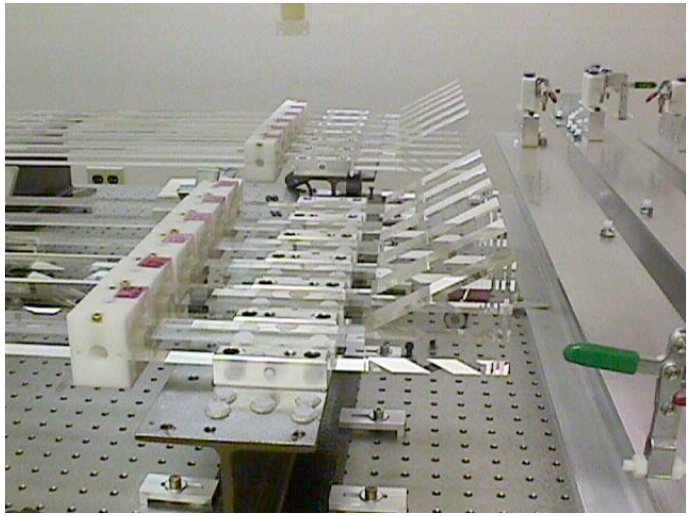
Requesting funding for GEM/timing detector readout electronics, the CRT support structure, and gas supply, as well as for hpDIRC prototype HV/LV power supplies and a DAQ PC plus travel for CUA/GSI to SBU.

Extra Material

QA of Disassembled Bars

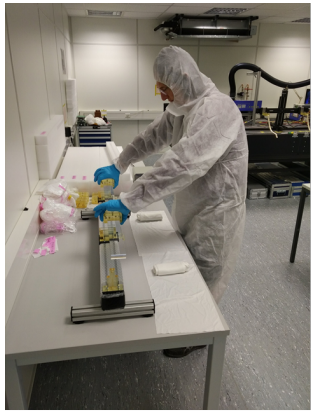
Technical risk: QA of the disassembled bars in laser setup:

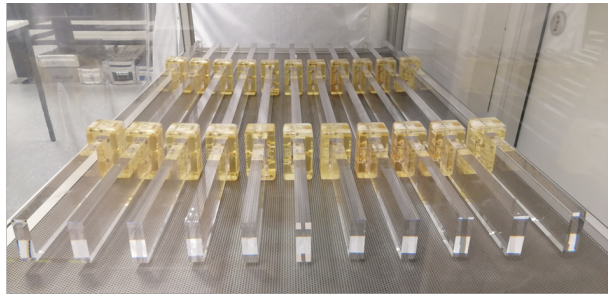
- BaBar DIRC bars were produced with 0.3-0.5nm surface optical finish
- Loss of optical quality would cause loss of photon yield and drop in PID performance
- Carefully evaluate all bars from first bar box, decide if disassembly strategy (decoupling into single bars) works or should be changed (keeping longer bar units)
- Expect to perform full scans on at least 10% of bars

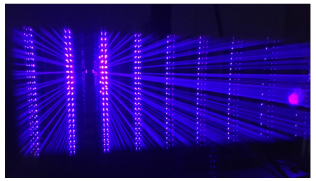


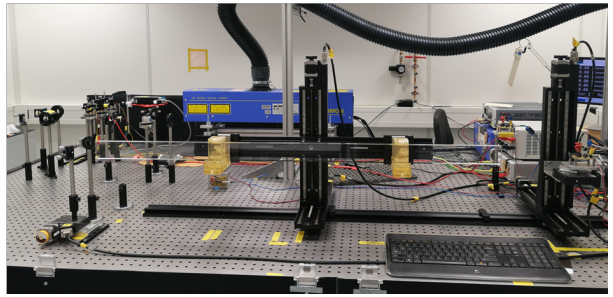
BaBar DIRC bars in SLAC lab (~1997)

PANDA Barrel DIRC bars in GSI lab (2021)





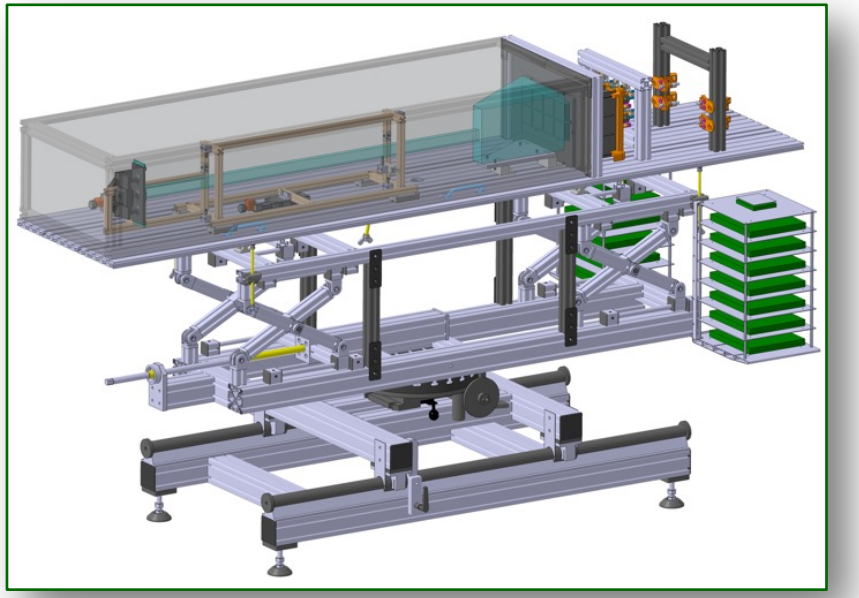


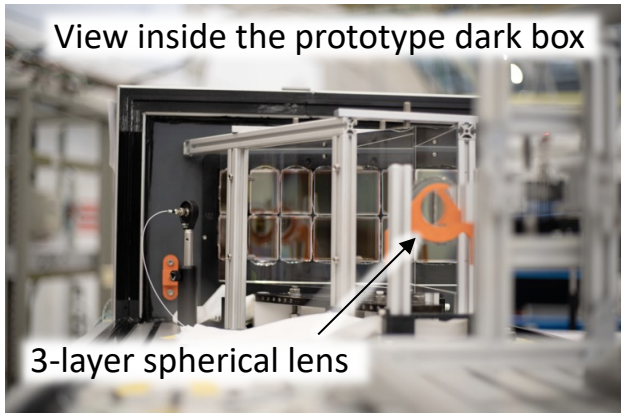


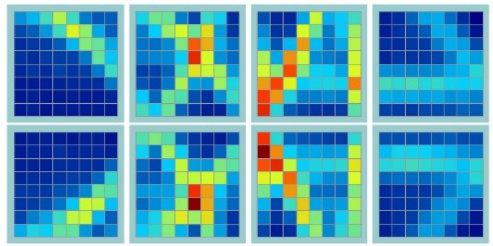
HPDIRC R&D: PROTOTYPE DEVELOPMENT

Technical risk: hpDIRC PID design validation

- Resolution and PID performance of system prototype
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)







Hit pattern

CERN 2018

HPDIRC R&D: PROTOTYPE DEVELOPMENT

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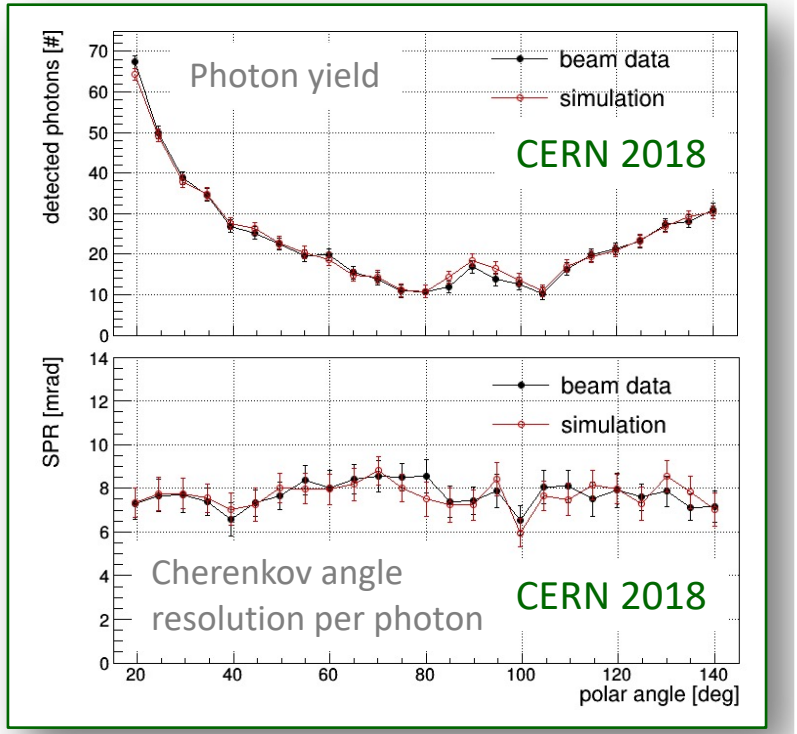
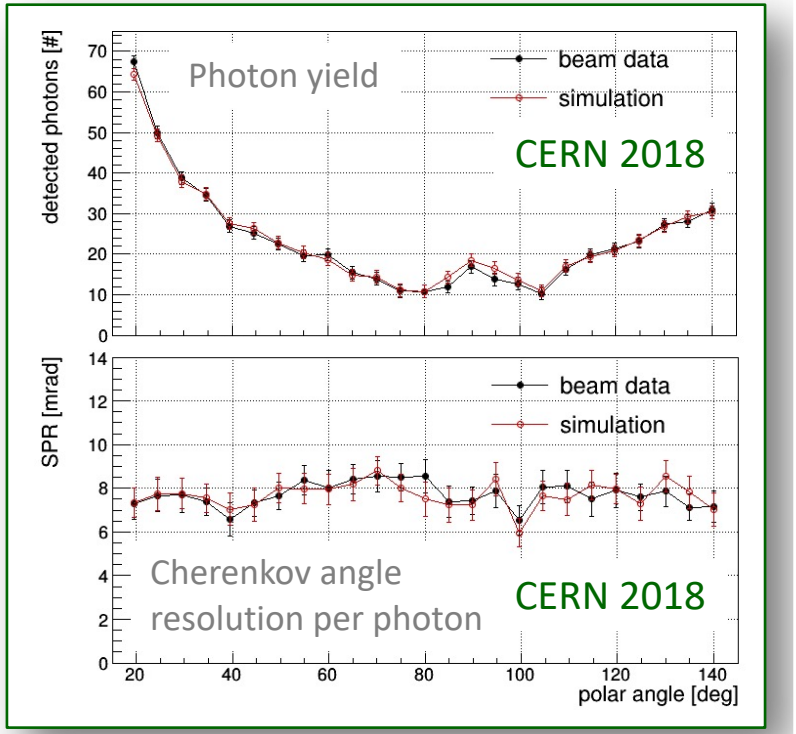


hpDIRC R&D: Prototype Development

Technical risk: hpDIRC PID design validation

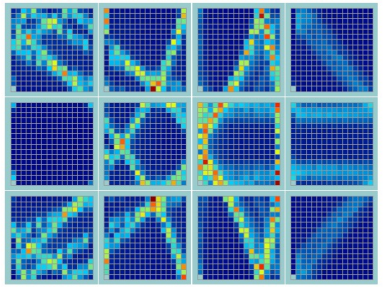
- Resolution and PID performance of system prototype
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)

- Used this simulation to predict PID performance of upgraded prototype
  (new MCP-PMTs and electronics, 3mm pixels, improved PDE, 100ps timing)
- Expected π/K separation at 6 GeV/c at 20°: 3.1 s.d.
- Upgraded PANDA Barrel DIRC prototype (new sensors, new electronics) capable of hpDIRC PID performance validation in particle beams

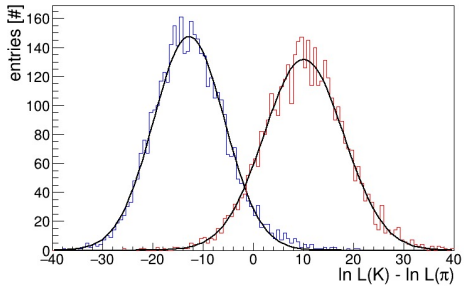


Geant simulation of upgraded prototype

Accumulated hit pattern



π/K separation at 6 GeV/c at 20°



HPDIRC PROTOTYPE: NUMBER OF PHOTOSENSORS

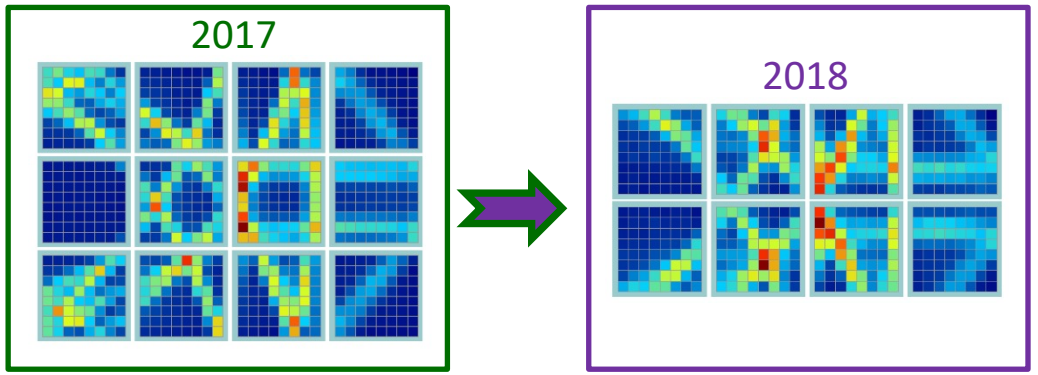
Example of validated cost/performance optimization, based on simulation study:

PANDA Barrel DIRC beam test at CERN in 2017 and 2018

2017: prism covered with 12 MCP-PMTs (3x4)

Simulation: 1/3 of the MCP-PMTs can be removed with no significant impact on PID ⟹ major cost savings.

2018: beam test with reduced coverage to 8 MCP-PMTs (2x4)



accumulated hit pattern

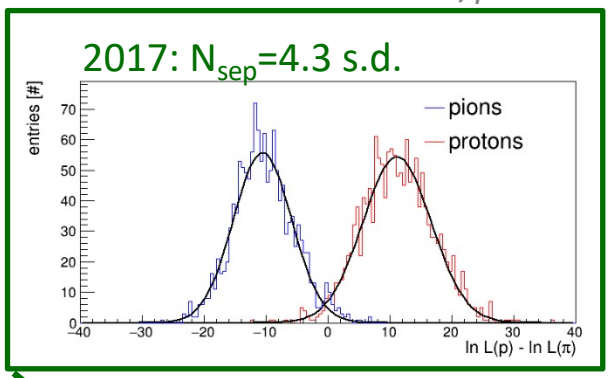
Found expected photon loss rate (30-40%)

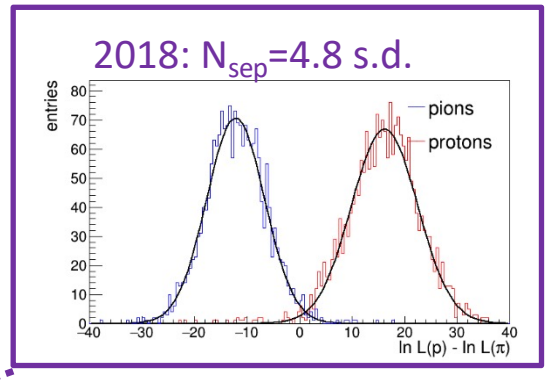
with no observable loss of PID performance.

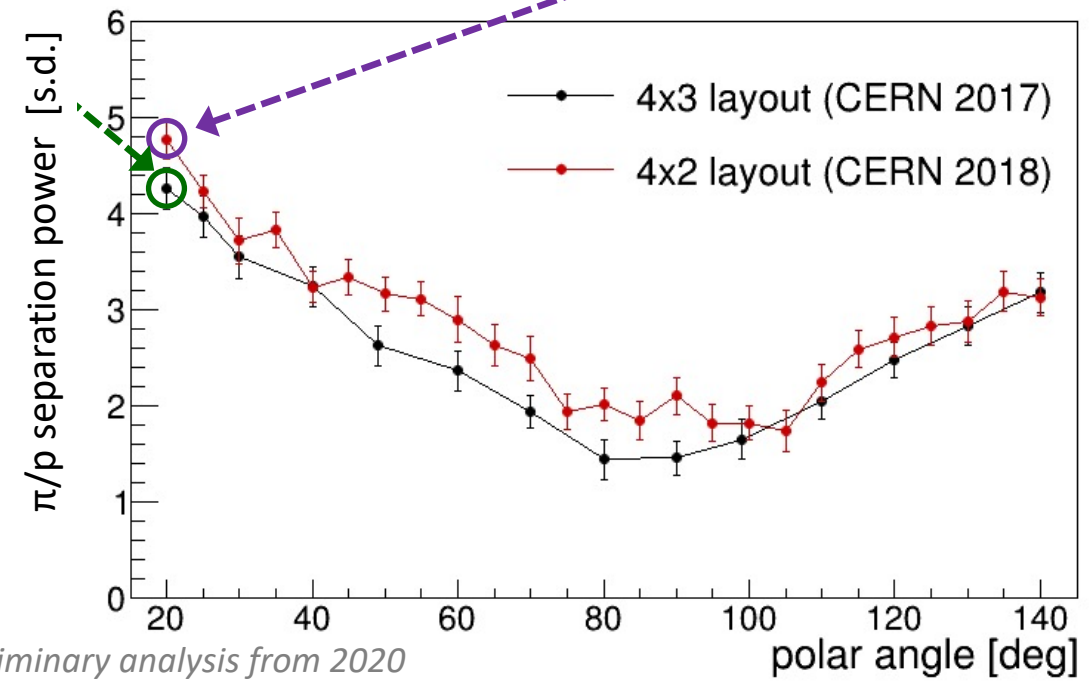
(Small improvement is due to better timing precision in 2018.)

beam data, 7 GeV/c

Note: π/p at 7 GeV/c ≈ π/K at 3.5 GeV/c







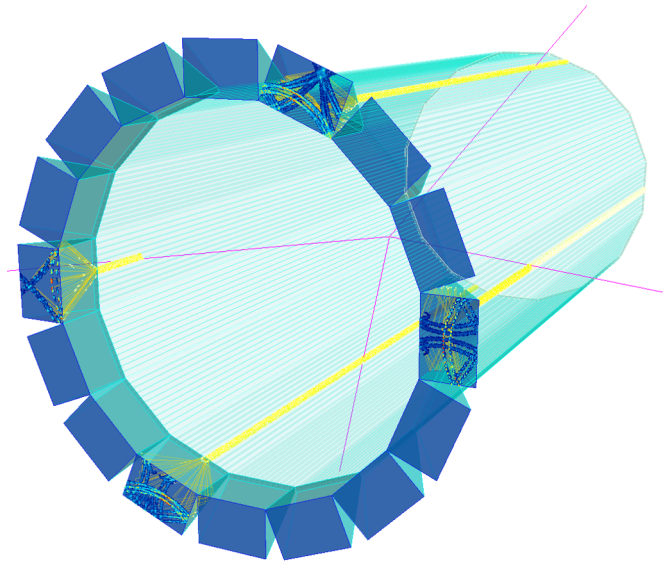
Preliminary analysis from 2020

HPDIRC PROTOTYPE: HYBRID RADIATOR DESIGN

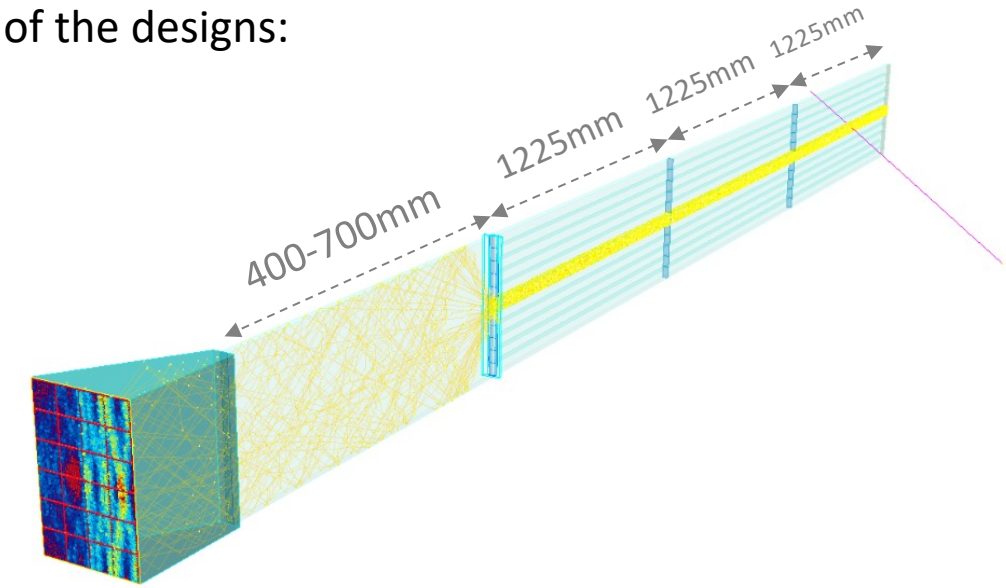
Opportunity: Cost saving and performance improvement

- EIC detector barrel length requires additional fused silica bars or plate to connect BaBar DIRC bars to prism
- Narrow bars could be obtained by cutting and repolishing BaBar DIRC bars or by ordering new bars from industry
- Alternative: use single short wide plate as transition light guide between BaBar DIRC bars and prism
- Would significantly reduce cost compared to new narrow bars and potentially improve hpDIRC performance
- Hybrid designs can be tested in prototype with no investment in new optics (using PANDA DIRC bar, plate and prism)

GEANT4 visualization of the designs:



Narrow bars in each sector



Hybrid of bars and plate in each sector